RESEARCH PAPER

Modeling of surface flux in Tongyu using the Simple Biosphere Model 2 (SiB2)

YAN Xiao-dong • LI Hui-yang • LIU Fei •
GAO Zhi-qiu • LIU Hui-zhi

Abstract: The modeling ability of a stand-alone version of the Simple Biosphere Model 2 (SiB2) was tested mainly through diagnosing the simulated latent heat (LE), sensible heat (H), CO_2 flux, and air temperature at the Tongyu field observation station (44°25′N, 122°52′E, 184 m elevation) of Coordinated Enhanced Observing Period (CEOP), where the land cover is cropland and grassland. In the whole year of 2003, the canopy height and the leaf area index was variable. During non-growth period, the surface would become bare, while during the growth period, the canopy height could reach 2.0 m high over cropland and 0.8 m high over grassland, respectively, and max leaf area index could reach 4.2 and 2.4, respectively. The model was initialized with measurement and driven by half-hourly atmospheric observations. The simulation values for 2003 were compared against measurements. Results show that the model is of a good ability of simulating the hourly latent heat (LE), sensible heat (H), CO_2 flux and temperature during the growth period. Moreover, the daily LE, H and CO_2 flux simulated by SiB2 could reflect their yearly change reasonably. However, the model may overestimate the H generally.

Keywords: cropland; grassland; Simple Biosphere Model 2 (SiB2); surface flux

YAN Xiao-dong (✉) • LI Hui-yang • LIU Fei
RCE-TEA, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing. E-mail: yxd@tea.ac.cn

LI Hui-yang • LIU Fei (✉)
Graduate University of Chinese Academy of Sciences, Beijing, P.R. China. E-mail: liufei@tea.ac.cn

GAO Zhi-qiu • LIU Hui-zhi
LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, P.R. China

Responsible editor: Hu Yanbo

Introduction

Grasslands occupy a significant portion of the earth's land area. Grassland ecosystems are diverse and have evolved in response to large seasonal and annual fluctuations in moisture, temperature, and grazing intensity (Knapp et al. 1998; Schuman et al. 2000). In recent decades, severe land degradation and desertification have occurred in China due to overgrazing, excessive mowing, and particularly crop cultivation, which are caused by the food demands for an increasing human population (Zhou 2002). The drought cropland and grassland in monsoonal Asia play an important role in the East Asia Monsoon energy balance (Fu et al 1999; Fu 2002; 2003). Degraded land provide a greater potential for sequester carbon. The improvement of degraded grasslands provides economic and sociological benefits as well. Tongyu flux station, a station in Coordinated Enhanced Observing Period (CEOP) (www.ceop.net) and founded in October 2002, was established for a long-term, continuous observation of the human activities and the exchange among surface atmosphere, lower-level atmosphere and biogeocenose. The constant data are very useful for understanding the impact of land use and water use on regional energy circulation and water circulation. The data obtained from this station have been used successfully to test the simulation abilities of several well known land surface models and ecosystem models, including IBIS model (Jiang et al. 2008), and BIOME-BGC model (Wang et al. 2006).

Atmospheric general circulation models are used for climate simulation and weather forecasting, requiring the fluxes of radiation, heat, water vapor, and momentum across the land-atmosphere interface that has been specified (Sellers et al. 1997). Land use and land cover (LULC) is the most important factor affecting the regional and global climate (Pielke et al. 1990; Pitman et al. 1999). The interaction between the vegetation cover and the lower-level atmosphere plays an important role in regulating the atmospheric circulation and then the various climate factors (Dickson et al. 1993; Irannejad et al. 1998).

The atmosphere, vegetation, and soil system are dynamically

coupled through the physical processes, which produce the transport of thermal energy and mass across the interface. Therefore, modeling based on physic is an important tool for studying the coupled system (Sridhar et al. 2002). In this study, the micrometeorological data at Tongyu flux station located in Northeast China was used to simulate latent heat, sensible heat and CO_2 with a stand-alone version 2 of the Simple Biosphere Model (SiB2) (Sellers et al. 1996a; 1996b). The SiB2 was originally designed to work with atmospheric general circulation models (GCMs). Randall et al. (1996) compared the results of a simulation of SiB2, which had been coupled to a GCM, against the results of a controlled simulation of SiB2, which had been coupled to a bucket surface hydrology model. They found that SiB2 produced warmer and drier surface and atmospheric boundary layer in the former work than the controlled work, resulting in increased surface sensible heat and decreased latent heat over the continents. Gao et al. (2004) used an off-line SiB2 to simulate daily and seasonal variations of the components of the surface energy balance and the CO_2 flux, though underestimating the sensible heat flux and latent heat flux by 10% and 11%, respectively. Gao et al. (2004) found that SiB2 could estimate soil wetness reasonably in the Tibetan prairie and still generated warmer (colder) ground surface in day-time (night-time) when they underestimate net radiation by 11%, and overestimated sensible, latent, and soil heat fluxes by 8%, 3%, and 11%, respectively.

In order to improve the current understanding of heat fluxes, and CO_2 exchange in semi-arid cropland and degraded grassland, we had designed an intensive cropland and grassland experiment in China's Jilin province since October 2003. This site is a typical semi-arid land in east-north china. Two different kinds of land covers, cropland and degraded grassland were considered to understand the characteristic of the semi-arid land.

Materials and methods

Study area

Measurements at Tongyu field observation station (44°25′N, 122°52′E, 184 m elevation), one of the referenced sites of CEOP, had been made since October 2002. This field occupied cropland with maize planted and degraded grassland either, and the sites in this field were flat, with approximate 5 km distance between any two sites. Soil at the experimented site was sandy loam, containing 60% sand, 35% clay, and 5% silt, respectively. Over the cropland, maize was cultivated from May to earlier October every year, so during the growth period the canopy height could be increased from 0.0 to 2.0 m, but during the other times the land cover was bare soil surface; over the degraded grassland, the grass maximum height could only reach 0.08 m.

Micrometeorological measurements

At every site, a 20-m meteorological observation tower was set up, and on the tower, wind speed (by Met one, 034 A-C), tem-

perature and humidity (by Vaisal, Hmp45C-L) were measured over five layers, and the wind direction (17 m, by Metone, 014A-L) was measured over 17 m layer. On the ground, the surface temperature (by temperature Hitester, APOGEE, IRTSO-P), air pressure and precipitation were measured. Upward and downward solar radiations (by CM21, Kipp & ZONEN) and upward and downward long wave radiations (by CG4, Kipp & ZONEN) were measured at 2.0 m and 3.0 m, respectively. Six layers soil temperature (2, 5, 10, 20, 50, 80 cm, by STPO1-L50, 107-L) and five layers soil volumetric Water Content (5, 10, 20, 40, 80 cm by CS616-L) were measured. Soil heat fluxes (by HFP01SC-L50) were measured at the soil depths of 5 and 10 cm. The sample frequency for those variations was 0.5 Hz. The eddy covariance instruments including a three-dimensional sonic anemometer (CSAT3), and humidity and CO_2 pulsation instrument (LI-COR, CS7500) were set at 3.0 m over cropland and at 2.0 m at grassland, respectively. The sample frequency was 10 Hz.

The micrometeorological measurements and fluxes were investigated during CEOP-EOP3 period (mainly in 2003).

SiB2 model

Overview
The SiB2 is a simple but realistic biosphere model for calculating the transfer of energy, mass and momentum between the atmosphere and the vegetated surface of the earth. It is designed for use in atmospheric general circulation models (Sellers et al. 1986). The detailed structure of SiB2 is described by Sellers et al. (1996a). The SiB2 uses two-stream approximation for modeling radiation. The SiB2 incorporate a realistic canopy photosynthesis-conductance model to describe the simultaneous transfer of CO_2 and water vapor into and out of the vegetation, respectively.

Forcing data
In the off-line Simple Biosphere Model 2, 10 meteorological forcing variables, including downward short-wave radiation, downward long-wave radiation, net radiation, vapor pressure, air temperature, wind speed, precipitation, air pressure, soil surface temperature, and soil deep temperature, were required. These forcing data, except for the precipitation, could be got basically by half-hourly measurements at Tongyu flux station. The precipitation could be provided on a day basis after July 2003. To meet the demand of the model, we incorporate the half-hourly vapor pressure and the daily precipitation to get the half-hourly precipitation as shown in Fig. 1, through assuming that the half-hourly precipitation was proportionate to the half-hourly vapor pressure daily because of lack of hourly measurement. Three layers (5 cm, 10 cm, and 20 cm) of half-hourly soil volumetric water content were also required. The reference height was determined to be 2.95 m high over cropland and 1.35 m high over grassland.

Parameter setting
SiB2 required users to input the soil and vegetation types. The soil at cropland and grassland contained mainly sand and loams,

therefore we selected the "sandy loam" type soil from Sellers et al. (1996b, in the Table 4). Over the cropland, maize was cultivated, but the degraded grassland was dominated by C_3 short-grass species. Therefore, together, the category was defined as "agriculture or C_3 grassland" (biome type 9) (Sellers et al. 1996b, in the Table 2). We obtained the time-invariant vegetation parameters from Sellers et al. (1996b, in the Table 5). The bulk boundary layer resistance coefficient C_1 and the ground to canopy air-space resistance coefficient C_2 were set to 15.1 and 131.0 for cropland, and 4.0 and 70.0 for grassland, respectively (Sellers et al. 1996b). During the whole year, the canopy heights changed from the minimum to the maximum, and then to the minimum again. The leaf area index, canopy greenness fraction, canopy cover fraction, canopy roughness length and canopy zero plane displacement also had changes. Considering the monthly mean leaf-area index data from the MODIS (ftp://primavera.bu.edu/pub/datasets), we combined the discontinuous observation with the logistic model (Lin et al. 2003), and then gave the variation of LAI in 2003 as shown in Fig. 2. The LAI had an abrupt decrease due to the harvest of maize. The canopy heights over the cropland and degraded grassland were shown in Fig. 3. We set the roughness length $Z_0=Z_2/7.6$ (Tanner et al. 1960), the canopy zero plane displacement $D=0.7Z_2$ (Stanhill 1969; Thom 1971), the canopy cover fraction (V) to 0.8 over cropland and 0.6 over grassland. The canopy greenness fraction (N) equaled to 1 during the growth period and 0 during the other times.
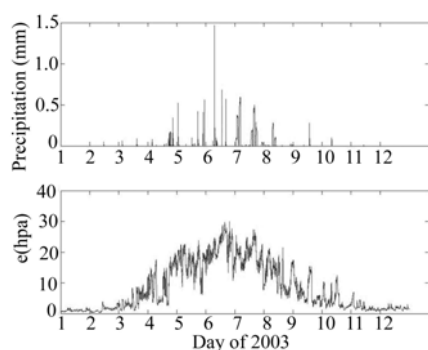

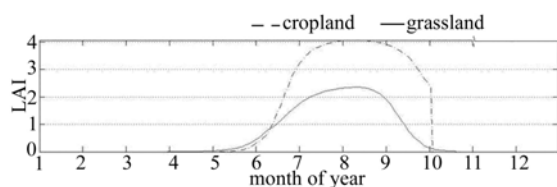
Fig. 1 Calculated half-hourly precipitation

Fig. 2 Yearly mean leaf-area index (LAI) data over cropland and degraded grassland.

Results

Hourly modeling of the growth period

Based on the half-hourly measurements, the half-hourly steps were used to simulate the annual changes over cropland and grassland. Because the flux changed mainly in growth period, we selected 213−233 Julia days of the year, in which period, maize grew to mature over the cropland and its leaf area index could reach 4.2. When maize matured, its respiration decreased. Fig. 4 showed the time series of the latent heat (LE), sensible heat (H), CO_2 flux and air temperature (T) modeled by SiB2 or obtained by the direct measurements. It was obvious that SiB2 had generated consistent temporal variations of LE, H, CO_2 flux and T. The squared correlation coefficients were shown in Table 1. The scatterplots of the modeled LE, H, CO_2 flux and T, and the direct measurements were given in Fig. 5. It was apparent that SiB2 overestimated LE in nighttime and H in all day. Moreover, it also estimated more CO_2 flux released by maize and soil land cover in nighttime. Nevertheless, it estimated the air temperature perfectly.
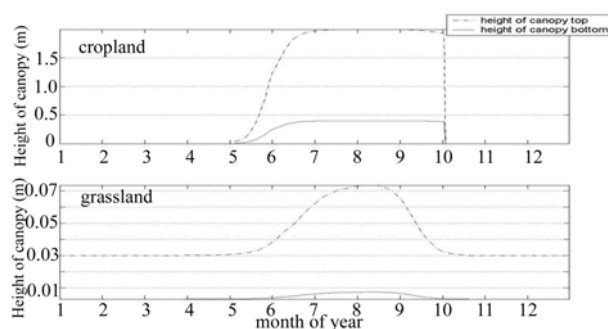

Fig. 3 Heights of canopy top (Z_2) and canopy bottom (Z_1) over cropland and degraded grassland, respectively.
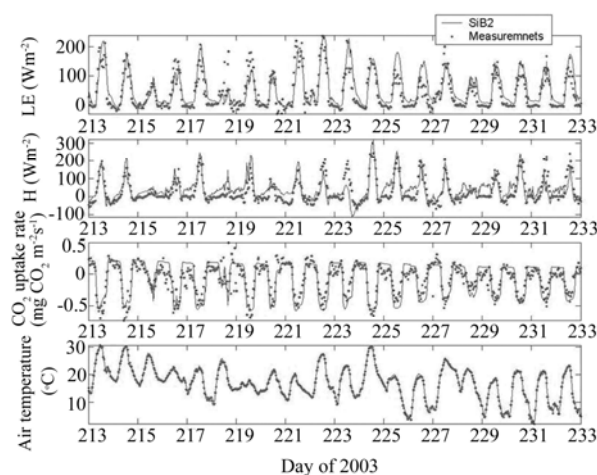

Fig. 4 Hourly change (213-233th days) of latent heat flux (LE), sensible heat flux (H), and CO_2 flux modeled using SiB2 against direct measurements over cropland.

Table 1. Squared correlation coefficients of daily latent heat (LE), sensible heat (H), CO_2 flux and temperature (T) in cropland and grassland for growth season.

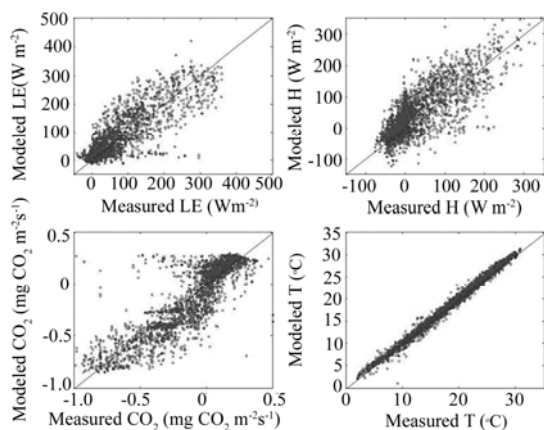| Land use types	LE	H	CO_2 flux	T
cropland	0.8977	0.809	0.864	0.9991
grassland	0.8911	0.8664	0.8063	0.9971

Fig. 5 Scatterplots of latent heat flux (LE), sensible heat flux (H), and CO_2 flux modeled using SiB2 against direct measurements over cropland.
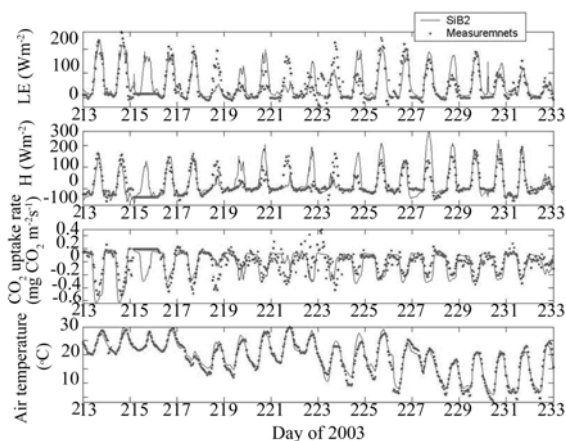

Fig. 6 Hourly change (213-233th days) of latent heat flux (LE), sensible heat flux (H), and CO_2 flux modeled using SiB2 against direct measurements over grassland.
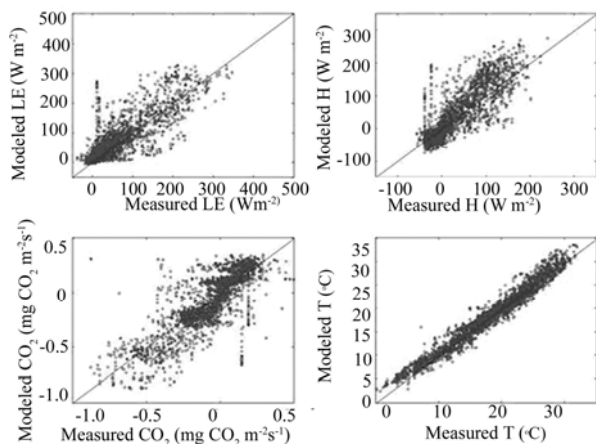

Fig. 7 Scatterplots of latent heat flux (LE), sensible heat flux (H), and CO_2 flux modeled using SiB2 against direct measurements over grassland.

Fig. 6 showed the comparison between the modeled and the direct measurements over grassland, and Fig 7 was its scatterplots. SiB2 overestimated the LE and the H. Although it overestimated the air temperature, its squared correlation coefficient reached 0.9971 as shown in Table 1.

Hourly modeling of mean day

The ability of hourly simulation in a day was investigated by comparing the modeled half hourly latent heat (LE), sensible heat (H), CO_2 flux and air temperature (T) with the several-day averaged value of the direct measurements. Figs. 8-9 showed that SiB2 had a good hourly simulating ability for cropland and grassland, and their squared correlation coefficients were shown in Table 2.

Table 2. Squared correlation coefficients of hourly latent heat (LE), sensible heat (H), CO_2 flux and temperature in cropland and grassland for growth season.

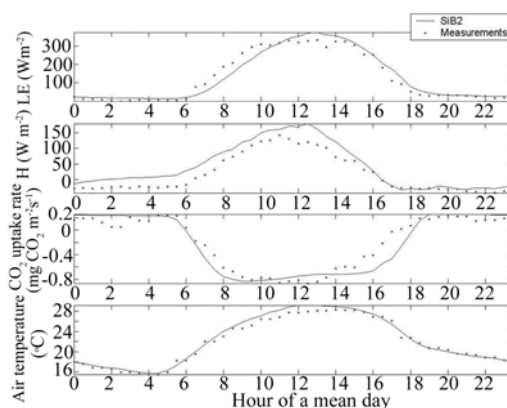| Land use types	LE	H	CO_2 flux	T
cropland	0.9857	0.9521	0.9634	0.9997
grassland	0.9907	0.9879	0.9703	0.9997

Fig. 8 Hourly change of a mean day over cropland (averaged from DOY (Julia days of the year) 200 to DOY 210).
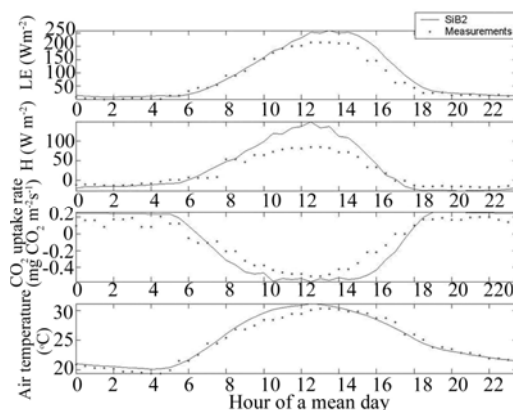

Fig. 9 Hourly change of one mean day over grassland (averaged from DOY 200 to DOY 210)

Fig. 8 showed the mean variations of DOY (Julia days of the year) 200−210, in which period, the maize grew rapidly with the strongest respiration, and its leaf area index could reach 4.2. This proves that SiB2 had done a good hourly simulation. It also had high squared correlation coefficients over cropland except for overestimating H (Table 2). In the nighttime, there was no photosynthesis of maize and no heat by radiation either, so the LE, the H, and CO_2 absorbed by maize and soil decreased to the lowest value in a day. When sun rose, the temperature near the surface rose and the photosynthesis began, so the LE and the H increased (reach their maximum at noon), and so did the CO_2 absorbed by the surface. However, at noon, the maize CO_2 absorption decreased sharply due to high temperature caused stomatal closure. All the variables would descend with the declining radiation in the afternoon. SiB2 could simulate all these process reasonably. SiB2 could also simulate this phenomenon over grassland.

Daily modeling

The half-hourly time steps were used to investigate the ability of daily simulation of the model. During a year, the characteristics of the land surface often changed with the variety of the radiation and the anthropic activities. Over the cropland, the maize was planted in May and harvested in early October, and during the other times the land was bare soil. The measurements in the first 45 days from 10 April to 15 May were discarded for its lack of measure and strongly anthropic activities. It is obvious that SiB2 consistently generated temporal variations of the LE, the H, the CO_2, and the T (Fig. 10). The squared correlation coefficients are shown in Table 3. The same variations were also shown on grassland (Fig. 11). SiB2 gave a perfect simulation of the air temperature. During late May and June, the rapid growth of the maize increased the model's disturbance. SiB2 also gave a reasonable estimate of the CO_2 flux, and the minus values represent the CO_2 absorbed by plants and soils. However, the measurement error in the non-growth period might occur due to less CO_2 exchange caused by less vegetation cover and low temperature.

Table 3. Squared correlation coefficients of daily latent heat (LE), sensible heat (H), CO_2 flux, and temperature in cropland and grassland for whole year.

Land use types	LE	H	CO_2 flux	T
cropland	0.8535	0.7353	0.7542	0.9998
grassland	0.9184	0.8539	0.5903	0.9981

Fig. 11 Comparison of latent heat flux (LE), sensible heat flux (H), CO_2 flux, and air temperature modeled using SiB2 against direct measurements over grassland.

The simulated and observed values had some obvious difference at some moment for the four parameters. For example, Fig. 10 showed a poor LE simulation. This might be caused by complex reasons such as the observation errors (almost all flux tower measurement in fact exists a problem: energy budget is not close, thus LE and H may have a gap to actual flux), the model limitation (some physical processes may be simplified incorrectly), and human activity effects (including possible irritation, fertilization and pasture, etc.)

Summary and conclusions

In this study, the modeled results of the energy flux and CO_2 flux were obtained over a cropland and degraded grassland in north-east China in 2003. The daily patterns of the SiB2 modeled latent heat flux (LE), the sensible heat flux (H), the CO_2 flux and the air temperature were consistent with the direct measurements during the growth period, especially with the day-averaged value. SiB2 showed a good simulation ability of the hourly changes, and also gave a reasonable simulation of the seasonal varieties in a whole year.

However, many gaps between modeling and observations inevitably exist. Besides observation methods and condition are imperfect, the model simplification is another key factor. For example, LE simulation can be closely correlated with soil heat process, which was approximately computed using forcing-restore method. In fact, this only is a first order approximate
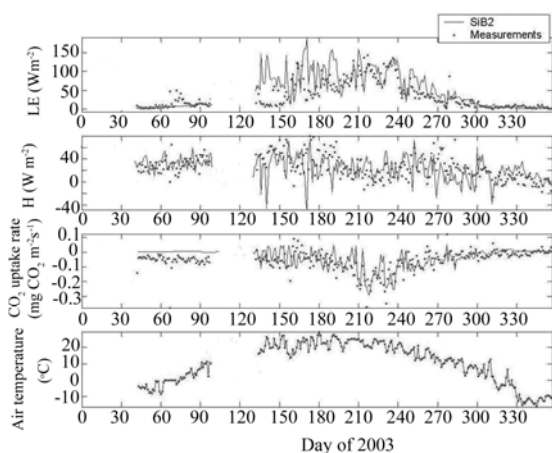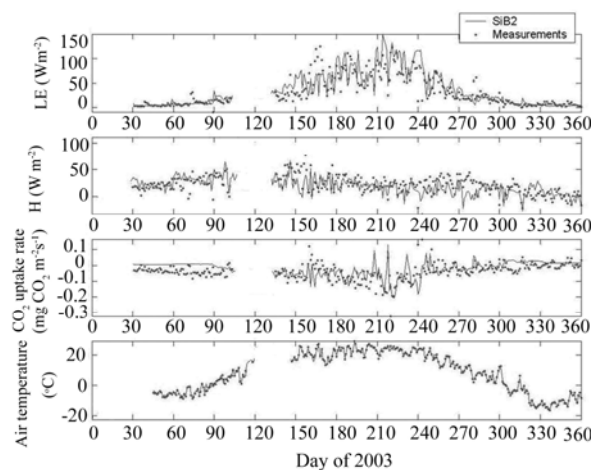

Fig. 10 Comparison of mean daily (24-hour) latent heat flux (LE), sensible heat flux (H), CO_2 flux, and air temperature (T) modeled using SiB2 against direct measurements over cropland.

and not suitable for real non-linear process. Hence, we think that soil thermo process and vegetation growth and physiological process should be improved for more realistic simulation of the water flux with heat flux in the future.

References

Dickinson RE, Henderson-Sellers A, Kennedy PJ. 1993. Biosphere–Atmosphere Transfer Scheme (BATS) Version1e as Coupled to NCAR Community Climate Model. *NCAR Technical Note,* TN-387 + STR, 72 pp.

Fu C, Wen G. 1999. Variation of ecosystems in East Asia in association with the seasonal, interannual and decadal monsoon climate variability. *Climatic Change*, **43**: 477−494.

Fu C. 2002. Can human-induced land cover change modify the East Asia monsoon system? In: Steffen W, Jäger J, Carson DJ, Bradshaw C. (eds.), *Challenges of Changing Earth*, Springer, pp133−136.

Fu C. 2003. Potential impacts of human-induced land cover change on East Asia monsoon. *Global and Planetary Change*, **37**: 219−229.

Gao Z, Chae N, Kim J. 2004. Modeling of surface energy partitioning, surface temperature and soil wetness in the Tibetan prairie using the Simple Biosphere Model 2 (SiB2). *Journal of Geophysical Research*, **109**, D06102, dio:10.1029/2003JD004089.

Irannejad P, Shao Y. 1998. Description and validation of the atmosphere–land– surface interaction scheme (ALSIS) with HAPEX and CABAUW data. *Global Planet Change,* **19**: 87−114.

Jiang Jifeng, Yan Xiaodong, Huang Yao, Guo Weidong, Liu Huizhi. 2007. Simulation of CO_2 and sensible/latent heat fluxes exchange between land surface and atmosphere over cropland and grassland in semi-arid region, China. *Journal of Forestry Research*, **18**(2): 114−118.

Knapp AK, Briggs JM, Hartnett DC, Collins SL. (eds.). 1998. *Grassland dynamics: Long-term ecological research in Tallgrass Prairie*. New York: Oxford University Press, 386pp.

Lin Zhonghui, Xiang Yueqin, Mo Xingguo, Li Jun, Wang Ling. 2003. Normalized leaf area index model for summer maize. *Chinese Journal of Eco-Agriculture*, **4**: 69−72. (in Chinese)

Pielke RA, Avissar R. 1990. Influence of landscape structure on local and regional climate. *Landscape Ecology*, **4**(2/3): 133−155.

Pitman AJ, Pielke RA, Avissar R, Claussen M, Gash J, Dolman H. 1999. The role of the land surface in weather and climate: Does the land surface matter? *Global Change Newslrtter*, **39**: 4–11.

Randall DA, Dazlich DA, Zhang C, Denning AS, Sellers PJ, Tucker CJ, Bounoua L, Berry JA, Collatz GJ, Field CB, Los SO, Justice CO, Fung I. 1996. A revised land surface parameterization (SiB2) for atmospheric GCMs. Part III: The Greening of the Colorado State University general circulation model. *Journal of Climate*, **9**: 738−763.

Sellers PJ, Mintz Y, Sud YC, Dalcher A, 1986. A simple biosphere model (SiB) for use within general circulation models. *Journal of Atmospheric Sciences*, **43**: 505−531.

Sellers PJ, Randall DA, Collatz GJ, Berry JA, Field CB, Dazlich DA, Zhang C, Collelo GD, Bounoua L. 1996. A revised land-surface parameterization (SiB2) for GCMs. Part I: Model formulation. *Journal of Climate*, **9**: 676−705.

Sellers PJ, Los SO, Tucker CJ, Justice CO, Dazlich DA, Collatz CJ, Randall DA. 1996. A revised land-surface parameterization (SiB2) for GCMs. Part II: The generation of global fields of terrestrial biophysical parameters from satellite data. *Journal of Climate*, **9**: 706−737.

Sellers PJ, Dickinson RE, Randall DA, Betts AK, Hall FG, Berry JA, Collatz GJ, Denning AS, Mooney HA, Nobre CA, Sato N, Field CB, Henderson-Sellers A. 1997. Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. *Science*, **275**: 502−509.

Schuman GE, Herrick JE, Janzen HH. 2000. The dynamics of soil carbon in rangelands. In: Follett RF, Kimble JM, Lal R. (eds), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Boca Raton: Lewis Publishers, pp. 267−290.

Sridhar V, Elliott RL, Chen F, Brotzge JA. 2002. Validation of the NOAH-OSU land surface model using surface flux measurements in Oklahoma. *Journal of Geophysical Research,* **107**(D20): 4418.

Stanhill G. 1969. A simple instrument for the field measurement of turbulent diffusion flux. *Journal of Applied Meteorology*, **8**: 509−513.

Tanner CB, Pelton WL. 1960. Potential evapotranspiration estimated by the approximate energy balance method of Penman. *Journal of Geophysical Research,* **65**: 3391−3413.

Thom AS. 1971. Momentum absorption by vegetation. *Quarterly Journal of the Royal eterological Society*, **97**: 414–428.

Wang Cao, Yan Xiaodong, Huang Yao, Liu Huizhi. 2006. With BIOME-BGC Model on the latent heat fluxes of the typical ecosystem: simulations in semi-arid area at Tongyu, Jilin Province. *Climatic and Environmental Research,*11(3): 405−412.(in Chinese)

Zhou Guangsheng, Wang Yuhui, Jiang Yanling. 2002. Global change and water-driven IGBP-NECT, Northeast China. *Earth Science Frontiers*, **9**(1): 198−216. (in Chinese)